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The objective of this work is to provide a basic understanding of the flow in the shock boundary layer interactions and of the mechanisms of their control. A parametric investigation was conducted to determine the effect of bleed configuration on the flow in the interaction region of an incident oblique shock with a turbulent boundary layer. Results of the numerical flow simulations were obtained for different slot widths, depths and slat angles over a bleed mass flow range between zero and choked conditions. The bleed results reveal a complex structure of compression expansion wave system over the bleed port entrance, and different levels of flow operation inside the slot. Code development for the implicit numerical solution of the two-dimensional compressible Navier-Stokes and K- $\varepsilon$ equations was completed. The code was used in the simulation of unsteady supersonic cavity flow and the results compared with experimental data.

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## ABSTRACT

The objective of this work is to provide a basic understanding of the flow in the shock boundary layer interactions and of the mechanisms of their control. A parametric investigation was conducted to determine the effect of bleed configuration on the flow in the interaction region of an incident oblique shock with a turbulent boundary layer. Results of the numerical flow simulations were obtained for different slot widths, depths and slat angles over a bleed mass flow range between zero and choked conditions. The bleed results reveal a complex structure of compression expansion wave system over the bleed port entrance and different levels of flow separation inside the slot. The effect of bleed configurations are compared in terms of discharge coefficient, total pressure recovery and the change in boundary layer characteristics downstream of the interaction.

Code development for the implicit numerical solution of the two dimensional Compressible Navier-Stokes and K-$\epsilon$ equations was completed. The code was used in the simulation of unsteady supersonic cavity flow and the results validated through comparison with experimental data.

# INTRODUCTION

The control of shock boundary layer interactions in inlets and nozzles can be accomplished through bleed and/or blowing in the interaction zone. In the case of mixed compression supersonic inlets, the bleed system design is critical to the efficient and stable operation of the system. Hamed and Shang (1) reviewed the existing experimental data for shock wave boundary layer interactions in supersonic inlets and other related configurations. According to this survey, there is enough experimental evidence (2, 3, 4, 5, 6, 7) to indicate that local bleed can control flow separation in shock wave/boundary layer interactions. There are disagreements (1) however among the different experimental results regarding the effects of bleed hole size (3, 4), and their location relative to the shock (2, 5, 6, 7). The experimental data in these studies is not sufficient to resolve these discrepancies since they mostly consist of static pressure distribution over the inner surfaces (1), and few velocity profile measurements (8, 9), upstream and downstream of the interactions.

The discrepancies among the different experimental studies is an indication of the complexity of the flow in these configurations. Based on the comparison of their computational results with the experimental data of supersonic inlet flow fields, Reddy et al (10) stressed the need for a detailed study of the effect of the individual bleed ports. Optimization of the bleed and/or blowing can only be resolved through a parametric investigation in which the bleed and blowing configurations are changed systematically. The large number of parameters and the difficulties in obtaining accurate flow measurements in the interaction zone precludes a complete experimental investigation. The purpose of the present study is to conduct a numerical investigation to characterize the details of the flow field in oblique shock wave boundary layer interactions with bleed. The aim is to use the results obtained in this investigation to understand the mechanisms involved in controlling the adverse effects of these interactions on the performance.

## A COMPARATIVE NUMERICAL STUDY OF THE FLOW IN OBLIQUE SHOCK/TURBULENT BOUNDARY INTERACTIONS

A comparative study (11) was conducted to assess the performance of four turbulence models(12, 15) with modifications (16-18) and four numerical codes (19-21) in predicting attached and separated flow conditions in shock wave boundary layer interactions.

Comparisons with existing experimental data for wedge generated incident oblique shock with a flat plate boundary layer (22, 23) and in a compression corner (23, 24) as used as the basis for assessing the code performance. The degree of agreement of the predicted separation length and the surface pressure distribution were taken into consideration together with the required grid refinement and the convergence characteristics. The findings of this investigation were reported in AFOSR Annual Technical Report titled "An Investigation of Oblique Shock/Boundary Layer Interaction Control" June 24, 1993.

## INVESTIGATION OF SLOT BLEED IN SHOCK WAVE/ TURBULENT BOUNDARY LAYER INTERACTIONS

A study was completed to investigate the effect of bleed through slots of different configurations on the flow in the interaction region of an oblique shock and a turbulent boundary layer. The incident shock was of sufficient strength ($\delta = 7.95°$) to cause flow separation in the turbulent boundary layer over the flat plate surface (at $M = 2.96$ and $Re \approx 1.09 \times 10^7$) in the experimental results of Law (22, 23). The flow simulations were accomplished by obtaining numerical solutions for the compressible Navier-Stokes equations with K-$\epsilon$ model in a domain that extended inside the bleed slot and upstream and downstream of the interaction region. The change in the bleed (suction) mass flow was accomplished in the numerical investigation through changing the static pressure at the bottom of the bleed slot over a wide range covering choked and unchoked flow conditions. The Park code (21) was used in the numerical simulation after it was validated for the unseparated and separated shock wave boundary layer interactions (11). The computed bleed results (25, 26) indicate a complex expansion and compression wave structure across the slot opening and different levels of flow separation inside the slot. The net effect of the bleed on the flow downstream is to reduce the momentum and displacement thickness and to increase the friction coefficient. The reduction in the momentum thickness downstream of the interaction increases with the increase in bleed mass flow, but eventually plateaus.

## BLEED THROUGH NORMAL SLOTS

A parametric study (25) was conducted for bleed through normal slots in the oblique shock/turbulent boundary layer interactions to determine the effect of slot depth and width on the flow field over the plate surface and inside the slot (25). The investigated slot widths ranged between 0.8 and 3.2 times the incoming boundary layer thickness before the interaction and their depths were 3 and six times their widths. The results indicated that the bleed discharge coefficient and total pressure recovery are not very sensitive to the bleed slot width. Both the discharge coefficient and the momentum thickness downstream of the interactioni were sensitive to changes in L/D and both improved as the aspect ratio increased.

The results of this investigation were presented as AIAA Paper 93-0294, titled "A Parametric Study of Bleed in Shock/Boundary Layer Interactions" at the 31st Aerospace Sciences Meeting in Reno, NV January 11-14, 1993 (Appendix A).

## BLEED THROUGH SLANTED SLOTS

A parametric study (26) was conducted for bleed through slanted slots in the oblique shock/turbulent boundary layer interaction to determine the effect of slot angle relative to the plate surface on the flow field and inside the slot. The investigated slant angles were 20°, 30°, 40° and 90° and the corresponding slot widths were 0.8 times the incoming boundary layer thickness before the interaction. According to the results obtained in this study, the effect of slant angle can be summarized as follows:

Bleed Discharge Coefficient

The discharge coefficient was very sensitive to slot angle. The slots with large angles started to bleed at lower pressure and choked at lower discharge coefficients. The slots with a smaller slot angles started to bleed at high pressures, choked at high discharge coefficient and exhibited less gradual change in the mass flow rate with bleed pressure.

Flow Field Characteristics

The expansion compression wave system across the slot opening changed with the slant angle. In the case of 90° angle the expansion wave at the slot's upstream corner was followed by bow shock originating inside the slot that stood in front of the slot's downstream corner. In the case of slated slot an oblique shock wave forms at the downstream slot opening, crosses the slot passages and impacts the upstream slot wall causing flow separation inside. A different mechanism, namely insufficient flow turning is responsible for the flow separation in the slot close to the upstream corner for the 90° and 40° slots which is associated with a large recirculating flow zone inside the slant. At bleed mass flow rates (15%) of incoming boundary layer) flow separation over the plate surface could be eliminated with slanted slots but not with normal slots, which requires much higher bleed mass flows through wider normal slots.

The results of this investigation were presented as AIAA Paper 93-2155 titled "An Investigation of Shock Wave Turbulent Boundary Layer Interaction with Bleed Through Normal and Slanted Slots" at the 29th Joint Propulsion Conference in Monterey, CA June 28-30, 1993 (Appendix B).

## ALGORITHM DEVELOPMENT FOR UNSTEADY FLOW SIMULATIONS

A numerical procedure was developed for simultaneous implicit numerical solution of the coupled k-$\epsilon$ and Navier-Stokes equations for compressible viscous flows (27). The numerical algorithm is based on the approximate factorization scheme of Beam and Warming for the strongly coupled set of equations. The scheme incorporates a new second order damping model which is based on the changes in both the pressure and the turbulent kinetic energy. This approach enhances the stability of the numerical solution and relieves the stiffness associated with the solution to the k-$\epsilon$ equations. Hence, with the elimination of the need for subiterative techniques (28), the developed algorithm is particularly suited for unsteady supersonic flow simulations. The detailed analysis will be presented as a paper titled "An Implicit Numerical Algorithm for the Strongly Coupled Navier-Stokes and K-$\epsilon$ equations at the 2nd (ISAIF) International Symposium on Experimental and Computational Aerothermodynamics of Internal Flows in Prague, Czechoslovakia, July 12-15, 1993.

NUMERICAL SIMULATIONS OF UNSTEADY SUPERSONIC CAVITY FLOW

Unsteady supersonic flow simulations over an open cavity (29) were conducted for one of the cases from the experimental study of Kaufman et al (30). At a free stream number of Reynolds number was $1.09 \times 10^6$ based on the cavity length of a 0.12065 meter. The cavity had a length to depth ratio of 5.07 and was 0.0635 meters wide. The results of the two dimensional flow simulation were compared with the experimental data along the clarity's mid span, since it was verified experimentally (30) and computationally (28) that the fundamental behavior of the oscillations is two dimensional. This work was presented as AIAA Paper 93-3031 titled "Numerical Simulation of Unsteady Supersonic Flow Using an Implicit Algorithm for the Strongly Coupled Navier-Stokes and K-$\epsilon$ Equations" at the AIAA 24th Fluid Dynamics Conference, Orlando, FL July 6-9, 1993 (Appendix C).

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